Analysis the impact of Energy Storage a shared Asset between DC Railway Network and Electricity Distribution Network

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Abstract— **European distribution networks and light-railway networks have been developed as independent networks, relying on the resilience and robustness of existing power supplies. This paper reports on findings of European Union H2020 funded E-LOBSTER project which in its concept, is proposing an innovative Railway to Grid (R+G) Management system which, combined with advanced power electronics, will be able to make the best use of the available energy on both the grids by increasing their mutual synergies and increasing the whole system efficiency. In this study, a sustainable solution, as a concept, represents a new type of electric infrastructure. In E-LOBSTER, electrical energy storage will play a shared asset between grid and railway. To investigate the solution, a real case study of urban metro line is chosen for simulation study. The challenges that distribution networks are facing with integration of high intake of EV charging facilities is providing an insight on the solution addressed in the paper. The results show the effectiveness of the proposed solution.**

Keywords—Light Railway, Electrical Distribution network, Battery Energy Storage System (BESS), Electric Vehicle (EV)

I. INTRODUCTION

In recent years, Battery Energy Storage System (BESSs) are gaining their importance due to emerging applications like especially electrification of the transportation sector and grid integration of volatile renewables. The need for storage systems led to BESS technologies performance improvements and significant price decline. This allows for opening a new market where BESSs can be an asset as a reliable and economic viable solution. Energy storage will play a key role in enabling the EU to develop a low-carbon electricity system [1]. Energy storage can supply more flexibility and balancing to the grid, providing a back-up to intermittent renewable energy. Locally, it can improve the management of distribution networks, reducing costs and improving efficiency. In addition, mobility is considered one of the key issues regarding the sustainability of modern cities, the flexibility of transport solutions and a smart integrated approach gain in importance as a key point. However, there are technical, social and economic barriers to its implementation which would also need to be addressed to create a sustainable solution [2].

Smart management of railway networks has already been subject of study and several projects have settled indications about its implementation in existing facilities. The origin of the very concept of railway smart management might come from the opportunity that regenerative braking offers. There are several studies that argue the train´s capability of energy regeneration is between 30% and 40% of the energy consumed. For several reasons, most of the metropolitan lines there are rheostat consumption losses of around 10-12%, which limits the real savings obtained by regenerative braking [3].

In the technology roadmap "European railway energy roadmap: towards 2030" the European Rail Research Advisory Council stated the importance of developing energy storage and battery technologies for future rail infrastructure. [4]. One of such an emerging market for BESS is R+G management system which will be investigated and demonstrated within E-Lobster project. In its concept, a sustainable solution, as E-Lobster concept, represents a new type of electric infrastructure. Regenerative energy is captured as the train brakes and is stored in BESS around the network. This energy can be drawn by the network to be supplied to railway or fed back to the grid or to support EV charging stations. In fact, the main objective of E-LOBSTER is to establish mutual synergies between power distribution networks, electrified urban transport networks and charging stations for electric vehicles [5]. With respect to this point, it is worth to mention that one major issue holding back the wider uptake of EVs is the perception that they cannot cover the desired distance without needing a recharge (range anxiety). This could either be due to the actual lack of charging infrastructure or to a lack of awareness that it exists. Although the charging infrastructure for EVs has been increasing at various speeds across the EU, similarly to the use of EVs, it is still insufficient in some Member States and there is lack of centralised information on all existing recharging points. The EU has taken measures to incentivise Member States to increase the number of recharging points, raise awareness of their existence and make them more standardised and interoperable. This paper will provide the results of a simulation study developed to analyse and compare the potential braking energy can be used to feed back to grid or to be stored in energy storage. In the following sections, the results of a real case study of urban metro line chosen for simulation study is discussed. Finally, paper concludes with closing remarks and next step.

II. SIMULATION PLATFORM

This section presents the framework of the two simulators under study: railway and the smart-grid simulators individually for a case study of Spanish Urban Metro Line.

A. Railway Network simulation

A railway simulator has been developed in [6-7] through MATLAB program and utilized in this paper to represent the Metro line under study. Metro Line is a 40.9 km circle line with 11 Traction Power Substation System (TPSS) and 28

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stations. The trains depart from Puerta del Sur and stop at every station; and finally return at Puerta del Sur. The total journey time is around 60 min. The rated operation voltage of this line is 1,500 V DC. The characterizations of traction system of the train are reported in Table I. The train is Series 8000 built by CAF and Alstom. The length of the train is 110 m with 6 carriages. Additionally, Table II provides the parameters of the DC line electrification system.

1) Single train simulation simulation

Using the data of Table I & II and considering the speed limit on the line, the speed and power diagram of each individual train is given by Fig. 1 and Fig. 2, respectively which are valid for trains travelling from Puerta del Sur to Parque Lisboa and vice versa. The trains acceleration shows the constant effort and constant power regions which are typical in the traction systems. The amount of cruising has been selected to keep the speed within the limit and guarantee that the train reaches the next station on time. In this model, there are no train delays or other causes disrupting the train service. Moreover, it has been assumed an identical dwelling time for all the stations and all the trains. The time step of the simulation has been set to 1 second.

TABLE I
Train traction characteristics

Parameters	Value/Equation
Overall train mass [tonnes]	180
Train formation	4 cars, M – S – R – M
Rotary allowance	0.08
Maximum acceleration rate [m/s]	1.0
Maximum braking rate [m/s]	1.0
Maximum traction power [kW]	2400
Maximum braking power [kW]	180
Maximum operation speed [km/h]	80
Maximum tractive effort [kN]	170
Dwell time [seconds]	30
Auxiliary power [kW]	80

TABLE II
Power network characteristics

Parameters	Data
Rectifier no load voltage [V]	1650
Rectifier rated voltage [V]	1500
Rectifier rating [MW]	2 x 3.3MW
Rail track resistance [Ω/km]	0.0145
Rail resistance per 2 tracks [Ω/km]	0.00725
3rd rail resistance [Ω/km]	0.0115

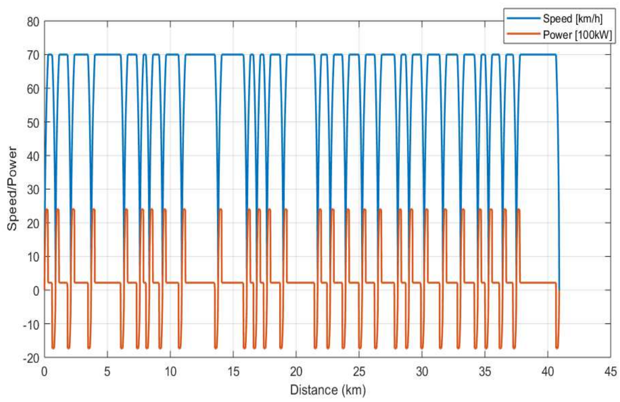

Fig. 1 Speed and profiles of a train travelling from Puerta del Sur to Parque Lisboa (up)

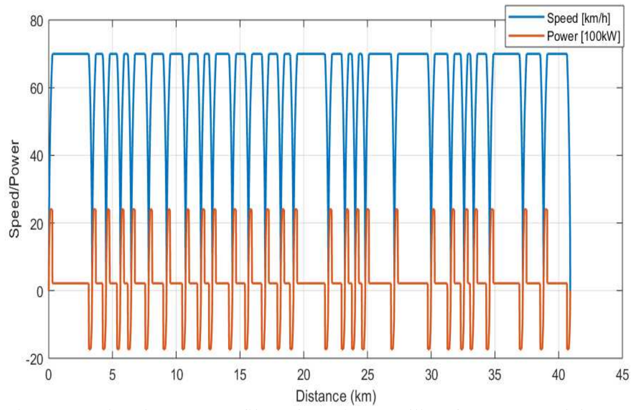

Fig. 2 Speed and power profiles of a train travelling from Puerta del Sur to San Nicasio (down)

The simulations are carried out when full service is running, i.e. excludes operations in the first hour and the last hour of the service when the number of trains is reduced.

2) Multiple train simulation (full-day)

Trains schedule operation of this Line is from 6:05 am to 2:00 am, which lasts 19 hours and 55 mins on working days.

The trains service for the full-day operation can be described as follows:

- 36 train cycles every 6.5 mins
- 112 train cycles every 7.5 mins
- 8 train cycles every 15 mins

The energy consumption for a whole-day operation is shown in Table III. The total energy consumption for a day is 103.92 MWh. The trains electrical braking energy is 70.65 MWh. 90.5% of available electrical braking energy is reused, which is 63.95 MWh per day.

TABLE III
Energy consumption for a whole-day operation

E_s	[MWh]	103.92
$P_{s,mean}$	[MW]	5.15
$E_{s,loss}$	[MWh]	3.12
$E_{t,loss}$	[MWh]	2.37
E_{aux}	[MWh]	28.09
$E_{traction,dem}$	[MWh]	134.28
$E_{traction}$	[MWh]	134.28
$E_{braking,avai}$	[MWh]	70.65
$E_{braking}$	[MWh]	63.95
η_{regen}	[%]	90.5%

The table has the following rows:

- E_s = Energy supplied by all the substations to the traction system within the headway time
- $P_{s,mean}$ = Average power supplied by all the substations within the headway time
- $E_{s,loss}$ = Energy losses of all the substations
- $E_{t,loss}$ = Energy losses of the electrification system (overhead supply and return rails)
- $E_{traction,dem}$ = Energy required by all the train to accelerate and coast
- $E_{traction}$= Energy actually drawn by all the train to complete the journey
- $E_{braking,ava}$ = Energy available from all the train for regenerative braking
- $E_{braking}$ = Energy actually regenerated by trains

- η_{regen} = Efficiency of regenerative braking, calculated as $E_{braking}$ / $E_{braking,ava}$

3) Multiple train simulation (different headway time)

The system energy consumptions within the headway period are shown in Table IV for various headway values, in which $P_{loss,mean}$ is the average power losses (substation and electrification) within the headway time . This refers to the energy drawn from all the TPSS during train service.

The results show that the energy consumption of the traction system increases when the headway decreases, as there are more trains running simultaneously on the line. In fact, the average power increases from 1.02 MW when the headway is 660 s to 5.16 MW when the headway is 120 s. Similar trend can be identified on power losses, but the ratio of the power losses to the respective power consumption is around 5% with various headways. It means the the energy losses vary with the headway changes, but not significantly. The substation loss is determined by the power from substation, and the transmission loss depending on the power flow in the network. The efficiency of regenerative braking decreases with the headway. In this case study, the efficiency of regeneration braking is high for this route, which is between 88% and 100%. One reason for the high efficiency of this Line is that the DC network is a long circle line, which allows the regenerative power to flow both sides.

TABLE IV
Energy consumption with various headways

Headway	[s]	120	180	240	300	360	420	480	540	600	660
E_s	[kWh]	618	616	616	636	617	643	621	622	656	675
$P_{s,mean}$	[MW]	5.15	3.42	2.57	2.12	1.71	1.53	1.29	1.15	1.09	1.02
$E_{s,loss}$	[kWh]	18.5	18.5	18.5	19.1	18.5	19.3	18.6	18.7	19.7	20.3
$E_{t,loss}$	[kWh]	12.5	10.7	10.6	12.4	11.7	12.7	12.5	14.4	11.9	13.9
$P_{loss,mean}$	[MW]	0.26	0.16	0.12	0.10	0.08	0.08	0.06	0.06	0.05	0.05
$E_{traction,dem}$	[kWh]	861	861	861	861	861	861	861	861	861	861
$E_{traction}$	[kWh]	861	861	861	861	861	861	861	861	861	861
$E_{braking,ava}$	[kWh]	453	453	453	453	453	453	453	453	453	453
$E_{braking}$	[kWh]	453	453	453	435	453	428	450	451	415	399
η_{regen}	[%]	100	100	100	96	100	95	99	100	92	88

B. Distribution Rialway Network Maintaining the Integrity of the Specifications

In modern railways, the DC traction substations are normally equipped with transformers and rectifiers, drawing electricity from distribution networks. Each traction substation is usually connected to an internal network (for example 15kV in Spain and 11 kV in UK) owned by the metro system operator. Due to the magnitude and variability of the traction load of a metro railway, the connection to the public grid must be at a higher voltage level. Connections to the public grid are therefore made at "Grid Supply Points" and then distributed to the traction substations. The common configuration of electrical railway network with connection to Distribution System Operator (DSO) substations for the metro line under study is illustrated in Fig. 3. The whole internal network is fed through 15 kV cables in traction substations and in transformation stations by different cables characteristics as provided in Table V. From point of connection to primary substations of DSO, Metro as qualified customer do not share feeder cables with other customers. In addition, qualified customers as Metro do not usually require a double feed because their own private medium voltage network provides the necessary redundancy. In this typical traction scheme, each TPSS in the internal network has a dual redundancy through two adjacent traction substations in a way that two different DSO substations are never connected to each other. In transformer stations, which are usually located closed to train passenger stations, there are 2 transformers 15kV to 0.4kV, of which one is connected, and one is in stand-by as a backup. These are the end points of the network. The whole network from DSO substation to end points of network is usually around 10km and the design is the same for the entire metro network.

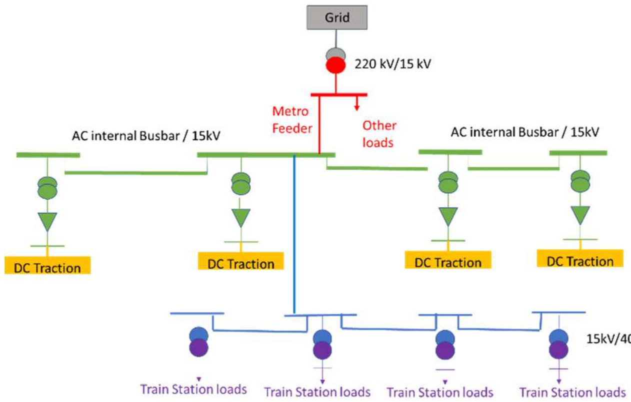

Fig. 3- Common configuration of the metro line under study with metro feeder connection to DSO supply points

TABLE V
Electrical characteristics of the AC cables of Line 12 of MDM

Cable	R(Ω/km)	X(Ω/km)	C(uF/km)
Red (main metro feeder)	0.0379	0.089	0.84
Green (TPSS feeder)	0.148	0.099	0.56
Blue (Train station feeder)	0.757	0.126	0.3

Five main DSO supply substations of 220kV/15kV are feeding power to eleven TPSS in the Metro Line under study, in which results of the simulation study for one of DSO substations named DSO RETAMAR is presented and discussed in detail in the paper. DSO RETAMAR is feeding four TPSSs which are typically called CAR, GET, CSR, and LEG. Instant real power telemetering data are gathered for a day at every 30 seconds from DSO RETAMAR. The boxplot of power consumption is illustrated in Fig. 4. As seen, consumption in trains is very irregular because they can change rapidly their state from braking or coasting at one moment to motoring at the following instant. Because of this, the power demanded in TPSSs is very variable too.

A simulation study has been carried out using grid simulator in MATLAB program. The measured traction power consumption of Fig. 4 is utilized in this simulation analysis in which it is assumed that the measured consumption power is divided equally between the four TPSSs connected to this DSO. The network is simulated assuming the reference voltage 1 p.u. at DSO RETAMAR substation busbar. The voltage profiles of four TPSS is calculated and the average of 0.997 p.u. can be considered for all four TPSSs, since all TPSS develop similar profiles for their estimated voltage as well. The boxplot of TPSS-CAR voltage profile is illustrated in Fig.5.

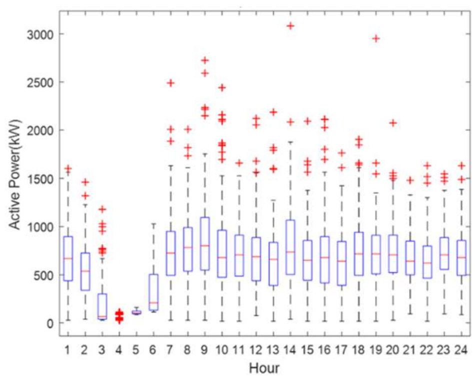

Fig. 4- Boxplot of DSO RETAMAR measured active power consumption of a working day

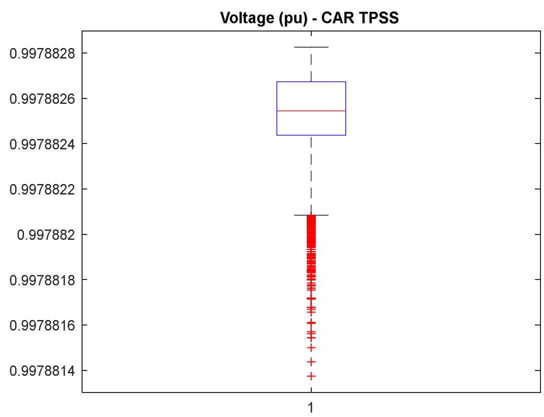

Fig. 5- Voltage of CAR TPPS- Simulation

Since all the TPSSs are connected to a 15kV busbar of Metro electrical internal network, so it is expected that voltage of all TPSSs follow the same pattern in which, the main impact on their voltage profiles comes from train loads. These results are in line with real voltage measurements as depicted in Fig. 6. It can be concluded form the simulation study and measured data that voltage level can be considered as fixed for all TPSSs in Metro electrical network at 0.99 p.u. for rail simulator.

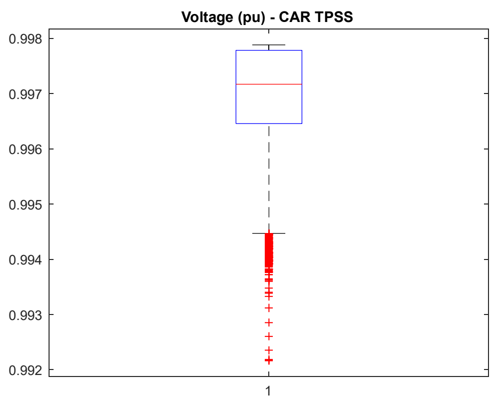

Fig. 6- Voltage of CAR TPPS- measurement

III. E-LOBSTER SOLUTION

With respect to E-LOBSTER, electrical energy storage will play a shared asset between grid and railway. It is a trade-off between electrical grid and railway network which services will be given priority in terms of energy efficiency of whole system. The control strategy will be developed through smart SOP (sSOP) as the brain of energy management system (Rail and Grid (R+G)) providing interexchange electricity towards mutual benefits. The sSOP is a parallel system to the rail and distribution networks, it is partially rated in terms of power and can limit its power flow at any operational condition through applying a current limit. The dynamics of the sSOP as a system are coupled to the rail voltage dynamics.

The concept of E-LOBSTER solution is illustrated in Fig.7. The Energy storage in E-LOBSTER solution can also support grid in up taking EV charging stations.

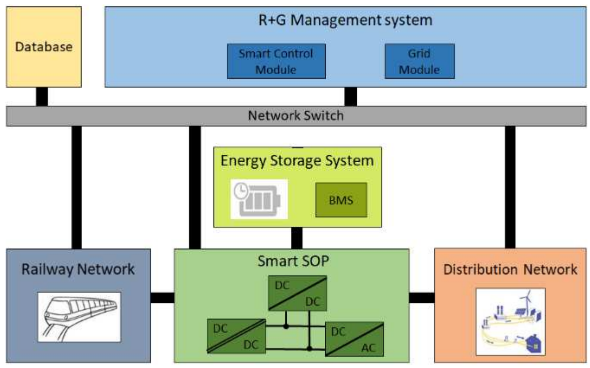

Fig.7- E-LOBSTER solution

A. *Impact of Energy Storage asset*

The energy usage profile of DSO substations feeding Metro Line reveals, it is a peak demand at rush working hour of day between 8:00–10:00 and in the evening between 16:00-18:00 as shown for DSO RETAMAR in Fig .8. Clearly, at rush hours, the energy consumption is higher as there are more trains in service but in the same time the regeneration efficiency is higher. Results of railway simulator in Table IV show that for headway of 120 S (2 min) the regeneration efficiency is around 98% in Metro Line. It means in rush hours; energy storage needs to provide peak shaving service to grid which will release some capacity of distribution network. In addition, when there are less train running and headway increase for example with headway of 660Sec (11 min) which will be at not busy times in late evening and early morning or at night, the regeneration efficiency will be decreased to 88%, so the braking energy needs to be stored in energy storage to increase the energy efficiency of railway.

The maximum, mean and minimum of hourly intervals energy consumption of five DSO substations are summarized in Table VI.

TABLE VI
Metro Feeder Energy Data

Hourly accumulated energy of DSO substations	Maximum (kWh)	Average (kWh)	Minimum (kWh)
1 (RETAMAR)	500	270	27
2	3920	2200	400
3	1880	1370	530
4	1200	850	130
5	750	520	150

It is worth mentioning that Gird Supply Points (GSP) or DSO substation in this study utilized for providing power to the DC railway network are generally not sole use sites, unlike those which provide power to the AC railway network. As such there are several additional feeders that connected to DSO substations feeding Metro lines. This limits the amount of control the railway infrastructure manager has regarding increasing loading on the equipment.

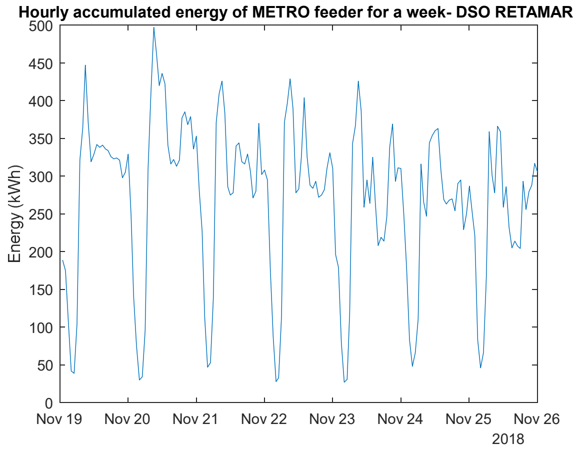

Fig.8- Hourly accumulated Energy of Metro Feeder connected to DSO RETAMAR Substation for a week

In the Metro Line under study, DSO has provided the maximum load of Metro Line and the maximum load of other loads fed by the same substation as summarised in in Table VII.

TABLE VII
DSO substation feeding METRO and other loads

DSO Substations	Transformer size	Transformer capacity (MVA)	Maximum of Metro Load	Maximum of other load on the same substation
1 (RETAMAR)	220kV/ 15 kV	50	2 MW, 0.64 MVAR (CAR) 6.5MW,2.08 MVAR (VALLE)	-
2	220kV/ 15 kV	50	6.9MW, 2.208MVAR	9.12MW, 3.16MVAR
3	220kV/ 15 kV	36.5	4MW, 1.28MVAR	9.21MW,2.5 MVAR
4	220kV/ 15 kV	36.5 & 50	2.2MW, 0.704MVAR	17.4MW, 4.31MVAR
5	220kV/ 15 kV	36.5	2MW, 0.64MVAR	10.81MW, 2.91MVAR

Table VI reveals DSO substation 2 & 3 respectively have the highest energy consumption and Table VII reveals DSO substation 4 & 5 have the highest other load consumptions. It means installation of ESS in all these locations will be beneficial from grid point of view. The difference between maximum and average of energy consumption in Table V provides an estimation of the amount of energy needed for peak shaving service of DSO substations. The higher energy consumption, the larger energy storage. In this case, the energy storage capacity will be highest for DSO substation 2 and lowest for DSO substation 5. In addition, the results of railway simulator of Metro Line show that the efficiency of regeneration braking is high for this route and the reason could be the DC network is a long circle line which allows regenerative power to flow both sides. Railway simulation of Metro Line considering reversible substations show in headway 120 S (2 min), the maximum power to be transferred to grid through reversible substations is around 2 MW through TPSS 4. In headway 660 S (11 min), the maximum power to be transferred to the grid is around 4.2 MW through TPSS 5. Although reversible substations are preferred in terms of energy efficiency, they practically have no impact on reducing the power peaks. However, with installation several BESS in Metro Line the efficiency of both railway and grid networks will be enhanced. It should be mentioned that although the biggest impact of the installation of ESSs comes from the increase in the energy efficiency and its associated reduction in the energy consumption, the reduction in the costs of the demand charge is also very important. The total amount of energy that can be stored in the BESS and the maximum power value that BESS can instantly receive or provide is a subject of study. The prototype is built on 200kW/200kWh energy storage and test results will be presented in future works.

B. Support of EV charging stations

EV charging infrastructure is one of the fundamental requirements for increasing the uptake of electric vehicles. There are several charging levels for EVs that reflect the power capability and charging duration. These levels have been standardized to reveal the EV slow or fast charging scenarios. The slow charging (typically up to 8 h-PHEV or 20 h-BEV) can be experienced at home or office areas whereas the fast charging (typically 15 min to 1 h depending on the battery size) at dedicated charging stations in commercial or public places [8-9]. With the current EV battery technology such as 24 kWh battery pack for Nissan Leaf, to recharge an EV will consume power almost the same as a single household in Europe or US per day. When two or three EVs are connected for charging purposes, there is a proportional growth of the energy usage. Hence, it reflects the increase in the consumption capacity to the existing grid infrastructure. In uncontrolled charging scheme, an EV starts charging immediately when connected to the electric power. If this additional load is not appropriately controlled, it can result to further aging of the power system equipment and tripping of the relays under rigorous overload conditions. In addition, different charging modes are available in market. The types of chargers installed can vary depending on the location of the site. Whether it is a motorway services station, a public street or workplace car park or even a home.

The results of rapid EV charging station demonstrated in Newcastle University Lab is presented in Table VIII for two different charging modes [10-11]. Clearly, rapid charging of 80kW will have a huge increasing demand on distribution grid.

TABLE VIII
Charge performance testing results

Charge mode	voltage (V)	Current (A)	Power (kW)	EV battery initial SOC (%)	EV battery final SOC (%)	Time used (minutes)
DC level 1	405	52	21	20	80	48
DC level 2	421	192	80	20	80	14

The railway case study revealed the potential of metro and light railway to support EV deployment through the recovering of trains braking storage in electrical storage. The deployment of EVs in the cities will demand a charging infrastructure. This Infrastructure could be developed for assuming that demand could be shared with other existing installation. The use of railway infrastructure may provide several benefits. There is a cost-reduction effect because of the use of an existing power supply installation. Furthermore, part of the regenerated energy that cannot be accepted by the railway system can be used by EVs improving the efficiency of the global railway-EV system.

Results of railway simulator for Metro Line under study presented in Table III, reveals the available braking energy not used is 70.65-63.95= 6.7 MWh for a whole-day operation which can be back to the grid or stored in energy storage or used for charging EVs. If it is considered the average daily energy consumed by a single Nissan-EV in a day can be estimated in 24kWh for guarantying an autonomy of 50-60km on a standard city cycle, then 279 EVs can be recharged everyday form the braking energy not used in Metro Line. If rapid charging of Nissan-EV 40kWh to be considered, then 167can be recharged. BESS in the E-Lobster solution will support EV rapid charging stations during peak demand of grid.

CONCLUSION

As mobility is considered one of the key issues regarding the sustainability of modern cities, the flexibility of transport solutions and a smart integrated approach gain in importance as a key point. Railways have an enormous potential in the implementation of smart management, considering their advantages of being permanently connected to the electricity grid and interacting with it. Nowadays, electrical railway systems are considered as an efficient and environmentally friendly solution for transportation system. Therefore, the management of multiple energy sources is an important issue for railway planning and operation. The arrival of modern railway technologies has allowed the implementation of regenerative braking systems, which can recover considerable energy from braking operation. The management of regenerative energy becomes vital considering the enhancement of railway operation. Energy storage devices can be used to store regenerative braking for reuse. Using energy storage systems not only increases the efficiency of the usage of regenerative braking energy, but also reduces the peak load demand for busy traffic.

This paper presented obtained results of the E-LOBSTER project which is aiming to provide a Rail & Grid (R+G) management system that uses a new smart soft open point to actively control the flow of energy through the DC railway network and the power distribution grid. Impact of BESS on the reduction of peak demand was studied through simulation studies of railway and distribution grid. Reduction of peak demand will have a great decrease on demand charge and in turn increases energy efficiency. In addition, E-Lobster solution will support distribution grid to accommodate EV integration within grid to develop smart mobility urban platform concept through integrating two transport systems EVs & Metro. In this concept, Metro can act as an aggregator to electrical grid. This meets the market requirement and will implement a big change and challenge for the metro companies. The E-Lobster project is an on-going project and will go through the next steps as the development continues to the demonstration in Lab and real substation environment.

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